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Application of a Computer Model to Set Heat Strain Threshold Limit Values: Evaluation During a Simulated Army Basic Combat Fitness Test

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Summary

The risk of exertional heat illness during military activities can be reduced by setting Threshold Limit Values (TLVs) using Wet Bulb Globe Temperature (WBGT) index. A study was undertaken to investigate if computer predictions of heat strain were accurate enough to set TLVs for military activities. Physiological strain during a simulated Army Basic Combat Fitness Test (treadmill walking at 6.8 km h^{-1} , 0% incline) in a warm environment (WBGT 24.3°C) was assessed in 20 apparently healthy male soldiers with no history of heat illness. Measured environmental variables, metabolic heat production, subject anthropometry, and estimated clothing thermal and evaporative resistances, were entered into a rational heat strain model. The range in measured rectal temperature (T_{re}) at the end of exercise was 37.7 to 39.3°C . T_{re} was correlated with exercise oxygen uptake ($r = 0.68$, $P < 0.001$). Differences between predicted and measured T_{re} after 60 minutes and at the end of the simulated Army Basic Combat Fitness Test, or point of subject withdrawal, were $+0.18$ (1 SD = 0.37) and $+0.03$ (0.48) $^{\circ}\text{C}$ respectively. It was concluded that computer predictions of heat strain have potential value for setting valid TLVs for military activities.

Introduction

Exertional heat illness (EHI) is an important issue for the Armed Forces of many nations (*eg* Minard, 1961; Epstein *et al*, 1999). UK Forces have about 100 hospital admissions each year, mainly occurring as a result of forced marching or other field exercise (Bricknell, 1996). The risk of EHI can be reduced by setting Threshold Limit Values (TLVs) using a heat stress index such as the Wet Bulb Globe Temperature (WBGT). TLVs must reflect the interaction of many factors such as physical fitness and other individual characteristics, clothing and metabolic heat production. However, as a consequence of the multitude of factors that cause heat illness, realistic guidelines do not prevent all heat casualties. Table 1 displays, in modified form, the current TLVs for the UK Armed Forces (Ministry of Defence, 2001).

TLVs are often based solely on experience of the human consequences of heat stress. This pragmatic approach carries an unquantified risk to exposed personnel. An empirical approach, based on human experimental data, would give low-risk, validated TLVs, but at a high resource cost. A more versatile method would be to use computer-based models of thermoregulation to predict heat strain and hence to set TLVs with reduced risk.

Although it is impossible for models to incorporate all variables involved in thermoregulation, they are reliable in describing heat exchange and useful to predict thermal strain particularly when metabolic activity remains constant over the time of the given heat exposure (Gonzalez *et al*, 1997). Such conditions arise in the British Army Basic Combat Fitness Test (BCFT) that each soldier must pass annually. The BCFT, which has been associated with cases of EHI, requires personnel to complete a 12.8 km loaded march (at least 4.8 km off tarmac) in a time of 2 hours, but not less than 1 hour 55 minutes. The purpose of this study was to compare the measured and predicted heat strain induced by a simulated BCFT to assess if it is feasible to set TLVs using computer-based models.

Table 1: UK Armed Forces Heat Stress Threshold Limit Values

Threshold Limit Values (°C WBGT)		
Not heat acclimatised	Heat acclimatised	Maximum work rate
32°C	No limit	Low <i>eg</i> Lying, guard duty, driving
26°C	30°C	Medium <i>eg</i> Marching 3.6 km h ⁻¹ 30 kg load
24°C	27°C	High <i>eg</i> Marching 5.6 km h ⁻¹ 20 kg load
20°C	25°C	Very high <i>eg</i> Marching 8 km h ⁻¹ no load, marching 5.6 km h ⁻¹ 30 kg load (equates to the Army Basic Combat Fitness Test)
30 minutes at 20°C	20°C	Extreme <i>eg</i> running in sports kit

These values are expressed for a 1-hour exposure with a minimum of 30 minutes rest after the activity. They apply to men and women of equal fitness, wearing a single-layer uniform with sleeves rolled up and without helmets. An individual is considered to be heat acclimatised if they have undertaken regular exercise for longer than ten days in the same environmental conditions as the proposed activity.

Methods

Subjects

Twenty, apparently healthy, male soldiers volunteered to participate in the study. Subjects were not heat acclimatised and had no history of EHI. Selected physical characteristics of the subjects are given in Table 2.

Table 2: Subject physical characteristics

	Age (years)	Height (cm)	Weight (kg)	Body fat (%)	VO ₂ max (ml kg ⁻¹ min ⁻¹)
Range	23-37	167-185	66.1-90.8	10.4-24.3	43.9-61.8
Mean (1SD)	30 (5.0)	176 (5.0)	80.7 (6.4)	17.4 (3.8)	53.8 (5.5)

Preliminary testing

Percentage body fat was estimated by skin-fold thickness at the biceps, triceps, subscapular and suprailiac sites (Durnin and Womersley, 1974). Aerobic fitness, expressed as maximum rate of oxygen uptake (VO₂ max), was measured during an incremental treadmill running test to volitional exhaustion.

Simulated Army Basic Combat Fitness Test

Activity: 120 minutes treadmill walking (incline 0%, speed 6.8 km h⁻¹) with 2-minute rest periods at 28, 58 and 88 minutes and 1-minute rest at 119 minutes. A 20.0 (1 SD = 0.3) kg backpack was carried. The mean oxygen uptake measured at 10 minutes was 2.0 (0.2) l min⁻¹. *Clothing:* The subjects wore cotton underpants and vest, lightweight combat trousers, woollen socks and leather boots. The clothing weight was 3.0 (0.3) kg; intrinsic thermal insulation (I_{cl}), 0.63 clo; Woodcock moisture permeability index (i_m), 0.55. *Environment:* Dry bulb temperature, 32°C; wet-bulb temperature, 21°C; relative humidity, 40%; water vapour pressure, 1.75 kPa; air speed, 2 m s⁻¹; WBGT, 24.3°C.

Subjects were encouraged to drink 6 ml kg⁻¹ body weight of water every 30 minutes during the simulated BCFT. Subjects were withdrawn if: rectal temperature (T_{re}) reached 39.3°C; heart rate attained 95% of the measured maximum for 3 minutes; they withdrew themselves; or 120 minutes had elapsed.

Physiological Measurements

T_{re} , mean skin temperature (T_{sk} ; Ramanathan, 1964) and heart rate were recorded every minute and averaged over 5-minute periods. Sweat rate (kg h⁻¹) was estimated from changes in nude body weight before and after the simulated BCFT, corrected for water consumed and urine produced. Expired air samples were obtained at 10 minutes to determine rate of oxygen uptake and rate of metabolic heat production (Weir, 1949).

Heat strain modelling

Measured environmental variables, metabolic heat production and subject anthropometry (height, body weight and % body fat), and estimated clothing thermal resistance and i_{m} , were entered into a rational heat strain model based on the Stolwijk and Hardy (1977) 25-node model of human thermoregulation. T_{re} was predicted for each subject at 1-minute intervals and compared with measured T_{re} at 60 minutes and at the end of exercise.

Statistical analysis

Linear regression analysis was undertaken on selected physiological variables. The alpha level was set at $P = 0.05$. Data are reported as mean values with 1 standard deviation (SD).

Results

12 subjects completed the simulated BCFT. 8 were withdrawn at times between 45 and 108 minutes: 4 with a T_{re} greater than 39.3°C; 1 with a heart rate greater than 95% of measured maximum; and there were 3 self-withdrawals due to headache and blisters. The range in measured T_{re} at the end of exercise was 37.7 to 39.3°C. At the end of exercise (or point of subject withdrawal), T_{sk} was 35.7 (0.9)°C; heart rate was 157 (19) beats min⁻¹; sweat rate was 1.3 (0.2) kg h⁻¹. T_{re} was not correlated with sweat rate, surface area:mass ratio, body weight or percentage body fat, but there was a linear correlation with exercise oxygen uptake ($P < 0.001$; $r = 0.68$) and maximum rate of oxygen uptake ($P < 0.02$; $r = 0.54$). The relationship between T_{re} and exercise oxygen uptake is shown in Figure 1.

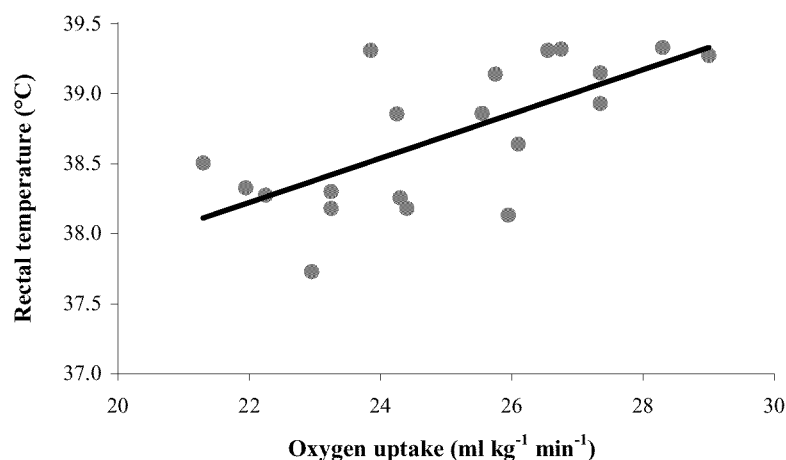


Figure 1: Correlation of rectal temperature with oxygen uptake for each of the 20 subjects

Measured and predicted T_{re} are displayed in Figure 2. The differences between predicted and measured T_{re} after 60 minutes and at the end of the simulated BCFT, or point of subject withdrawal, were +0.18 (0.37) and +0.03 (0.48)°C respectively.

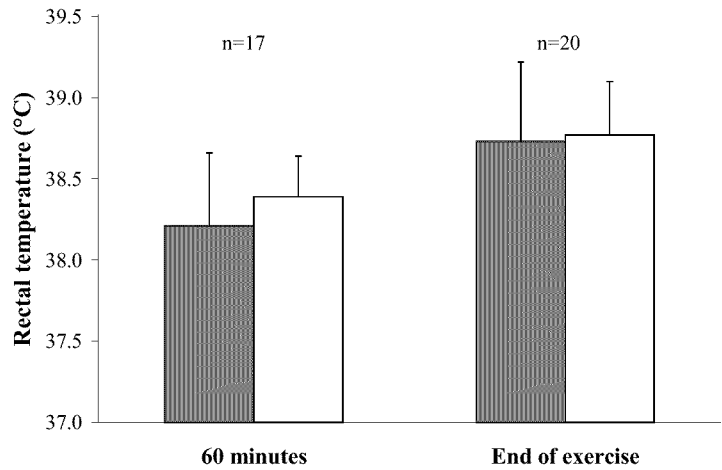


Figure 2: Measured () at the end of the exercise period for each subject (1SD). Data at 60 minutes are for 17 subjects; data at the end of exercise are for 20 subjects.

Two subjects (A and B) had a rate of rise of T_{re} ($T_{re\ rate}$) at 45 minutes more than 2 SD outside the mean of the other 18 subjects and were deemed to be heat intolerant. $T_{re\ rate}$ was $2.6\ ^\circ\text{C h}^{-1}$ in subject A, $2.1\ ^\circ\text{C h}^{-1}$ in subject B and $1.3\ (0.4)\ ^\circ\text{C h}^{-1}$ in the remaining 18 subjects (Figure 3).

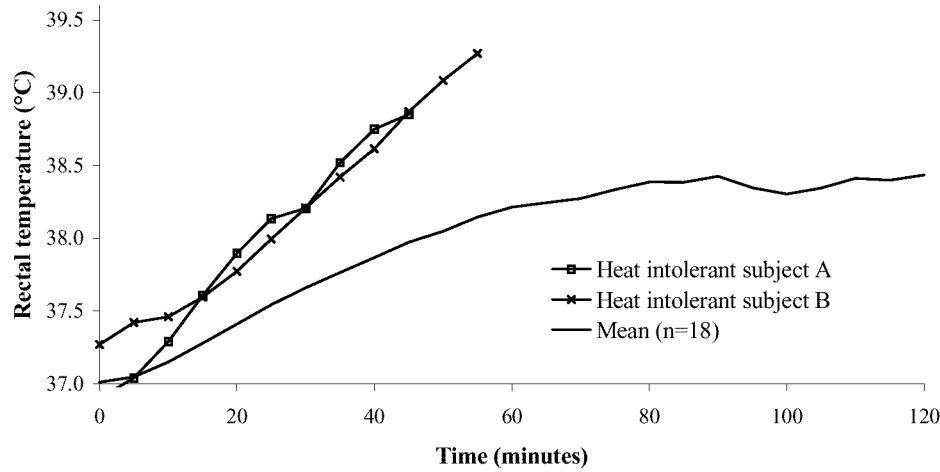


Figure 3: Rectal temperature during the simulated Basic Combat Fitness Test. Data to 45 minutes are for 18 subjects. Thereafter subjects began to withdraw. 12 subjects completed 120 minutes.

Discussion

There were large inter-subject differences in measured heat strain, which is typical of a cohort of otherwise healthy individuals. This variability was attributed, in part, to differences in metabolic efficiency during load carriage, as oxygen uptake during load carriage was correlated with T_{re} .

Two subjects appeared to be heat intolerant. These findings may relate to low aerobic fitness and high metabolic heat production in subject A, and impaired sweat loss in subject B. Subject B also had a high surface area:mass ratio, which has been correlated with heat strain (Havenith, 1995). Discussion of these

subjects is beyond the scope of this paper. Computer models cannot simulate the thermoregulatory responses of individuals, so such 'outliers' must be accounted for in TLVs by using wide confidence intervals.

Predicted mean T_{re} for the cohort was similar in magnitude and variance to measured T_{re} . Although it is impossible for computer-based models to incorporate all the variables involved in thermoregulation, these predictions show the degree of accuracy that can be achieved. We consider this sufficient accuracy to show that computer-based models have potential value for setting TLVs for other military activities.

Acknowledgements

This study was funded by Technology Group 5 (Human Sciences and Synthetic Environments) of the UK Ministry of Defence Corporate Research Programme.

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